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Science & Technology

USSR: Earth Sciences

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SCIENCE & TECHNOLOGY

USSR: EARTH SCIENCES

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Soviet-American Naval Arms Control Experiment Viewed

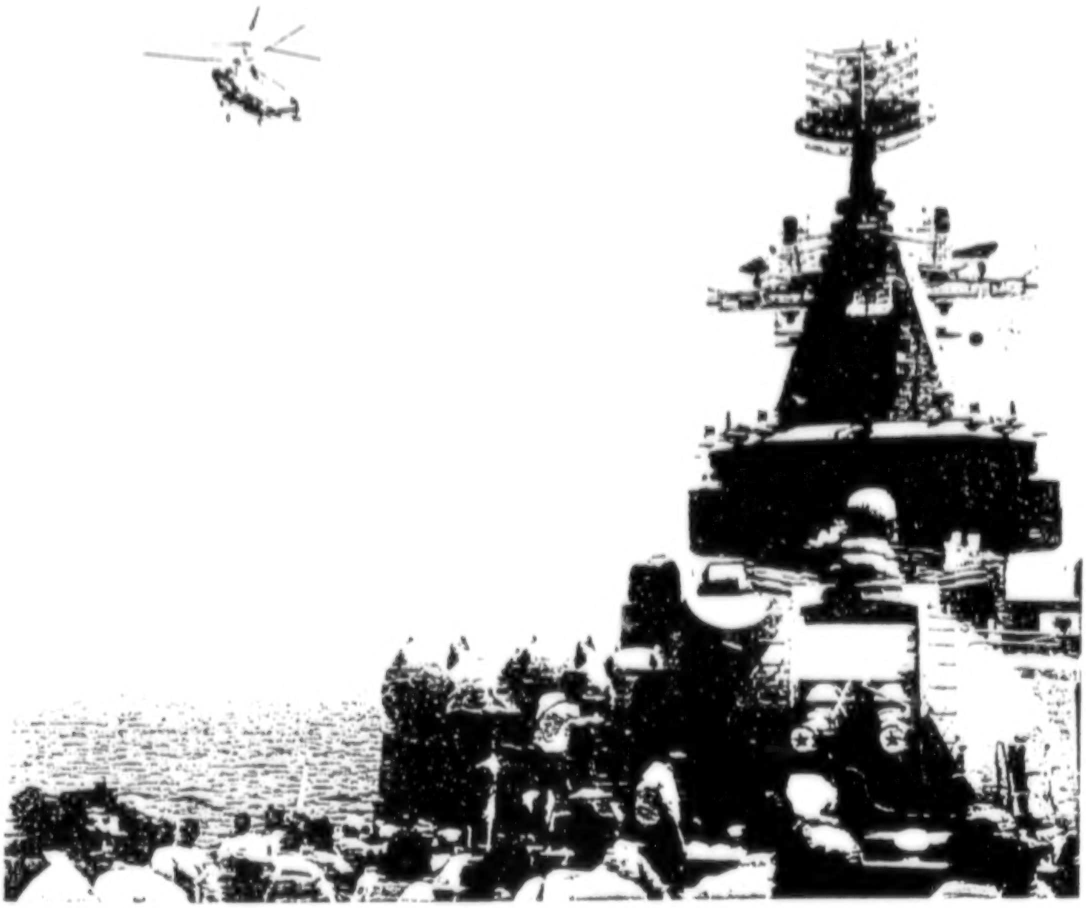
917N0038A Moscow PRIRODA in Russian No 9, Sep 90 pp 3-12

[Article by Academician V. L. Barsukov, director, Institute of Geochemistry and Analytical Chemistry imeni V. I. Vernadskiy, USSR Academy of Sciences, V. S. Karpov, candidate of physical and mathematical sciences, head, Nuclear Hydrophysics Section, Institute of Geochemistry and Analytical Chemistry imeni V. I. Vernadskiy, USSR Academy of Sciences, and O. P. Shcheglov, senior scientific specialist, Institute of Geochemistry and Analytical Chemistry imeni V. I. Vernadskiy, USSR Academy of Sciences: "Science Involved in the Process of Relaxation of World Tensions"]

[Text] A mutually acceptable agreement on restrictions on the deployment of long-range nuclear-armed sea-launched cruise missiles is now being worked out within the framework of the intergovernmental negotiations between the USSR and the United States on a 50% reduction in strategic weapons. This process obviously involves a search for effective methods making it possible to detect the presence of missiles with nuclear warheads on ships. In the course of the negotiations, the Soviet government proposed the implementation of joint experiments for checking the possibilities of conducting this kind of inspection aboard a surface ship using available equipment for the detection of nuclear weapons on the basis of radiation fields. However, this proposal was rejected by the Americans, who stated that in such cases radiation monitoring methods are inadequate for two reasons: there is the possibility of shielding and (or) concealment of a nuclear weapon beneath a ship's deck; a nuclear weapon could be stored on shore until a threatening situation developed. In addition, it was noted that the US Navy command did not consider it desirable to have Soviet inspectors aboard American warships and the US Department of Energy feared that the measurements made by Soviet inspectors might tend to reveal special design features of American warheads.

However, the Committee of Soviet Scientists in Defense of Peace and Against the Nuclear Threat came forward with a proposal for a joint experiment on a nongovernmental level. The idea of such an experiment was proposed by Ye. P. Velikhov early in 1988 and was supported by the Federation of American Scientists Against the Nuclear Threat. By early 1989 the USSR Academy of Sciences and the US National Committee for the Protection of Natural Resources worked out and coordinated a program for theoretical and field research which

would make it possible to evaluate the possibility of developing equipment for the detection and monitoring of sea-launched nuclear weapons.



The first experiment within the framework of this program was carried out in July 1989 in the Black Sea aboard the missile cruiser "Slava," which a half-year later served as the site for Soviet-American negotiations at a higher level off the coast of Malta.

Its final results were summarized early in December 1989 at a joint seminar in Washington. They were presented in a joint statement by American and USSR scientists which noted: "...although the Black Sea experiment is only the first step in studying the possibilities and limitations involved in using various kinds of monitoring techniques, it confirms the conviction of American and Soviet scientists that the organization of acceptable means and methods for monitoring sea-launched cruise missiles with nuclear warheads, without contravening international law and the laws of our countries, is entirely possible."

Academician V. L. Barsukov, director, Institute of Geochemistry and Analytical Chemistry imeni V. I. Vernadskiy, USSR Academy of Sciences. Vice president of the International Society of Geological Sciences. A specialist in the area of space chemistry, ocean geophysics, geology and geochemistry of ore deposits. The winner of the USSR State Prize. Published many articles in "Priroda."

V. S. Karpov, candidate of physical and mathematical sciences, head, Nuclear Hydrophysics Section, Institute of Geochemistry and Analytical Chemistry imeni V. I. Vernadskiy, USSR Academy of Sciences. Studies ocean geochemistry and nuclear-physical methods of analyzing matter, radioecology.

O. P. Shcheglov, senior scientific specialist, Institute of Geochemistry and Analytical Chemistry imeni V. I. Vernadskiy, USSR Academy of Sciences. Areas of scientific interest -- nuclear-physical methods of analyzing the content and properties of matter, space chemistry.

Then a joint call was made to the governments of the United States and the Soviet Union to provide maximal support and assistance to the efforts of scientists in investigating the possibilities for developing and using effective methods for monitoring sea-launched nuclear weapons. Thus, science, which once participated in the arms race at the behest of politicians, can now really facilitate the process of relaxation of world tensions.

What is a nuclear weapon and what forms of evidence can be used to detect it? An answer to these questions will make it possible to comprehend the essence of the methods and to evaluate the prospects for developing technology for monitoring sea-launched nuclear weapons.

Nuclear Weapons as Source of Radiation

It is well known that the isotopes ^{235}U and ^{239}Pu can be used as the principal components in a nuclear weapon. The ^{235}U content in natural uranium is 0.7%, and the other 99.3% is accounted for by ^{238}U, in which fission can take place only under the influence of fast neutrons. For the fabrication of a nuclear weapon, natural uranium must be enriched and its ^{235}U content must be increased to at least 20%. The uranium used in the United States for military purposes contains more than 90% ^{235}U.

The second fissionable isotope used in nuclear weapons is ^{239}Pu, which simply does not exist in nature. It is obtained by bombarding natural ^{238}U with neutrons in a nuclear reactor.

The technologies for fabricating nuclear weapons are still kept secret, and it is difficult to assume that in the immediate future we will have access to any reliable information concerning them. From publications in the open press, it is possible to obtain only general ideas concerning models of nuclear devices [see Footnote 1]. With respect to "demasking" factors, we can divide them into two classes:

I. Model A (atomic bomb) based on: ^{235}U, obtained from natural uranium (model AU); ^{235}U, extracted from reprocessed nuclear fuel (model AU*); ^{239}Pu (model AP); mixtures of ^{239}Pu and ^{235}U (models APU, APU*).

II. Model H (hydrogen bomb), as a "fuze" using A models of different types; to obtain great (100-1000 kt) blast powers -- up to 100 kg Li_2DT or Li_2D_2 is used. These are charges of great caliber and mass.

Thus, any modern nuclear weapon uses some combination of such fissionable materials as ^{235}U, ^{239}Pu, and in some cases also natural ^{238}U, which increases the explosive force of the nuclear weapon. In this case there is no need for perfectly pure isotopes. In a "uranium" bomb, for example, up to 7% ^{238}U is allowed, whereas in a "plutonium" bomb from 3 to 6% ^{240}Pu is allowed.

By virtue of their physical properties, these isotopes should reveal themselves by the different kinds of radiation, of which two -- neutron and γ radiation -- can be detected at a distance. Their penetrating capability is such that the structural materials of the missile warhead and launcher are not a significant obstacle for them. Gamma quanta are emitted in the decay of all fissionable materials, whereas neutrons in large quantities appear only during the decay of ^{240}Pu. The energy of γ-quanta (E_γ) is determined by the structure of the emitting nucleus; accordingly, from the spectrum of γ-radiation, as from "fingerprints," it is possible to make an unambiguous identification of the type of nuclear matter used in the warhead of a cruise missile. This makes it possible, without direct access to cruise missile launchers, to detect the presence of a nuclear weapon in them and to determine its type.

For example, for the identification of ^{235}U, it is sufficient to detect γ-radiation with E_γ = 185 keV (the strongest line per decay). The characteristic energies of γ-radiation of ^{239}Pu are 375 and 414 keV. In addition, in a nuclear weapon (models AP or APU) it is possible to detect γ-radiation with E_γ = 2615 and 583 keV which are characteristic of the radioactive isotope ^{208}Tl. It accumulates over time in plutonium, primarily due to the decay of ^{236}Pu, ^{240}Pu present in the plutonium charge in small quantities. (In American models of nuclear weapons the ^{240}Pu content is 3-6%.)

Neutrons are formed during the spontaneous fission of uranium and plutonium. Their mean energy is about 1 MeV, but the total number is dependent on the model of the nuclear weapon and varies within a wide range: from 10 to 100 n/s in the AU model to 10^4-10^5 in the AP and APU models in which there is an admixture of ^{240}Pu, which is particularly prone to spontaneous fission.

The neutron flux emanating from a nuclear weapon interacts with parts of the structural materials of the nuclear weapon carrier and the ambient medium, slowing to thermal energies. And such neutrons are already effectively trapped by nuclei of elements in the warhead or ambient medium, thereby forming a secondary γ-field with E_γ of up to 6-7 MeV.

The detection of neutrons aboard a ship may indicate the presence of fissionable materials belonging directly to both a nuclear weapon and to the nuclear fuel used in the nuclear power plants of surface ships and submarines.

The spontaneous fission of uranium and plutonium is also accompanied by the emission of γ-quanta. With allowance for all the nuclear processes transpiring in a nuclear warhead, the integral flux of γ-quanta beyond the limits of the shell of a nuclear weapon for models of the AU and APU types is estimated at 10^6-10^7 γ/s. However, these estimates may differ, especially in the downward direction, from the actual flux of γ-quanta because we do not know either the degree of purity of the initial nuclear materials or the precise design of the nuclear weapon and its location in the cruise missile; these factors reduce the fluxes of neutron- and γ-radiation.

The fluxes of neutron- and γ-radiation from a nuclear weapon do not exceed the level of the natural background of the medium, and detecting them requires ultrasensitive nuclear-physical methods.

Nuclear-Physical Methods for Detection and Identification of Nuclear Weapons

Due to the great diversity of processes involved in the generation of γ-radiation by a nuclear weapon, its energy spectrum is virtually continuous in a broad range of energies from eV to several MeV. In addition, it must be taken considered that, while passing through parts of the nuclear weapon carrier of different density on the way to the detector, the spectrum of primary γ-radiation from a nuclear weapon experiences changes (degrades) due

to three principal factors: photoeffect (knocking of electrons from the inner shells of atoms), accompanied by the absorption of γ-quanta; Compton effect (scattering of γ-quanta on electrons), accompanied by an energy decrease of the primary γ-quanta; generation of electron-positron pairs when $E_\gamma > 1.02$ MeV.

The contribution of each of these processes to the change in the spectrum of primary γ-quanta is dependent on both their energy and on the atomic number of the material, its density and thickness, as well as on the location of the source of γ-radiation in the nuclear weapon carrier. After several scattering events the primary γ-quanta seemingly "forget" their history, and at a distance equal to the length of the free path of a γ-quantum (for example, for E_γ = 600 keV in the atmosphere this is about 100 m) the energy spectrum from the source will be determined for the most part by scattered γ-quanta with considerably lower energies than for primary γ-quanta. As the distance from the source increases, the relative contribution of the scattered γ-quanta to the total spectrum of radiations increases. In this connection the energy spectrum of γ-radiation from a nuclear weapon at different distances will have a complex dependence not only on the type of warhead and the structural features of its placement on the carrier, but also on external factors: influence of the atmosphere, interfaces of media, and the geometry of the relative arrangement of the source and detector of the radiation.

In order to develop effective technologies for detecting, identifying, and monitoring the presence of nuclear weapons on ship platforms, the most promising approach is to use a remote-contact method of multichannel spectrometer measurement employing detectors of different types. The remote method can ensure detection and location of nuclear weapons on the basis of γ- or neutron radiation, whereas the contact method makes it possible to identify the detected source as belonging to a nuclear weapon with a certain type of warhead on the basis of the energy of γ-quanta.

The recording of γ-radiation from a nuclear weapon is done with scintillation and semiconductor detectors, but gas ionization detectors filled with ^3H or special inorganic scintillators are used for neutrons.

Scintillation detectors based on sodium and cesium iodide, bismuth germanate, or cadmium tungstate have nearly 100% efficiency in the recording γ-quanta with an energy up to 3 MeV. They operate quite reliably and can measure up to 10^4 cm^2. However, their energy resolution is low (tens of keV when E_γ is about 1 MeV). On the other hand, semiconductor detectors (based on germanium) have a high energy resolution, but due to their small size they are less efficient in comparison with scintillation detectors. In addition, they require cooling and are more complex to operate. Accordingly, depending on the problems to be solved, it makes sense to use both types of detectors in a certain combination.

Energy resolution is one of the most important parameters of γ-spectrometers. In the hierarchy of characteristics, the next most important are γ-spectrometer response and background.

Response is a factor representing the conversion of the density of the flux of γ-quanta (or particles) entering the detector into the output signal frequency. It is dependent on the characteristics of the detector, the type, spectral composition and directivity of the detected radiation flux, and also on the parameters of the electronic units used in the γ-spectrometer; it is determined experimentally.

The gamma-spectrometer background is the "noise" level, which consists of the intrinsic detector background (constant component) and the background recorded by the detector from the ambient medium in the absence of a valid signal (variable component). The intrinsic background of the γ-spectrometer is determined by direct and scattered γ-radiation, α- and β-radiation from natural and artificial radioactive impurities present in the material of an active element of the detector and the structural parts and electronic units adjacent to it. The variable component of the background is attributable to the contribution of γ-quanta from natural and artificial radioactive elements scattered throughout the surrounding medium and also cosmic radiation components. The contribution of γ-radiation from the surrounding medium to the total level of the background recorded by the γ-spectrometer may vary in a wide range and is estimated experimentally under specific instrument operating conditions. The variable component of the γ-background of the medium is the main interference which reduces the efficiency of the use of γ-spectrometer methods for remote detection and pinpointing of nuclear weapons on the basis of their γ-radiation.

Accordingly, for the construction of efficient and noise-immune systems for the remote detection of weak fluxes of γ-radiation from nuclear weapons, use is made of different methods to ensure the optimal choice of detection devices and systems for the collection and processing of data on a real-time basis. We will examine one of the possible ways of building a system for detecting nuclear weapons on the basis of their γ-field.

Principles for Constructing System for Detecting and Identifying Sea-Launched Nuclear Weapons

The optimal strategy in the continuous search for the anomaly of a γ-field from a nuclear weapon in the atmosphere (or in the surface water layer) using the method of direct γ-spectrometer measurements, synthesized on the basis of the scintillation method for recording γ-quanta, can be computed theoretically using the Neumann-Pearson test [see Footnote 2]. In actual practice the process of detecting the anomaly of the γ-field from a nuclear weapon with a selected (or stipulated) probability of reliable detection involves making a decision as to whether the anomaly of the γ-field associated with a nuclear weapon is present whenever the momentary intensity

of the γ-field (number of recorded pulses N_{ba} during a certain observation time interval τ exceeds the established threshold N_{thr}, based on the admissible probability of a spurious detection of a nuclear weapon γ-field. We will assume, for example, that the parameters of the observed γ-field and background at the γ-detector output correspond to a Poisson distribution with the parameters $N_{ba} = \sigma_{ba}^2$ (where N_{ba} is the mean background counting rate and σ_{ba}^2 is the background dispersion). [Note: in all cases N is an averaged value.] Then the probability of an erroneous decision regarding the detection of an anomaly of the γ-field associated with a nuclear weapon is evaluated in the following way:

$$\alpha = \exp(-2N_0^2/\sigma_\Phi^2),$$

where $N_0 = N - N_{ba}$ is the value of the effect recorded during the time τ. [Note: The Greek subscript on σ is for "ba" for background.] The ratio N_0^2/σ_{ba}^2 is the "quality factor" of the γ-detector.

On the other hand, the value of the recorded effect at the output of the γ-detector can be defined as $N_0 = A \times S(E) \times \tau$, where A is the intensity of the flux of γ-quanta from a nuclear weapon; S(E) is the response of the γ-detector in a certain energy range; τ is the observation interval.

Now it is possible to evaluate the threshold response of the γ-detector and the system as a whole; this response characterizes the capacity of the spectrometer to detect the minimal flux of γ-quanta from an object at a given range during the observation time τ against the background N_{ba}, with the dispersion σ_{ba}^2, with a stipulated probability α of an erroneous decision on the detection of the γ-field from a nuclear weapon:

$$A_{min} = \sigma_\Phi^2/\tau\sqrt{2} \cdot S(E) \cdot (\ln \alpha)^{1/2}.$$

An analysis of this expression shows that in order to improve the threshold response of the γ-spectrometer it is necessary to reduce the ratio $\sigma_{ba}^2 S(E)$. This can be done either by improving detector response or by reducing the level of the intrinsic detector background (for example, using materials with a low radioactive impurity content or by reducing the influence of the background component of the surrounding medium).

The first approach is more effective. The second has limitations that are attributable to the fact that, in the most informative energy ranges of the spectrum of γ-radiation from a nuclear weapon (0.1-0.5 MeV), the contribution of the background component of the ambient medium may exceed the intrinsic detector background level by 2-3 orders of magnitude. However, reducing background by selecting those energy ranges in which the contribution from the medium background is minimal (from 2 MeV or more) may result in a decrease in the useful component of the γ-field from a nuclear weapon or even total loss of it. As a rule, in this case different methods are used for rejecting the medium background. For example, the detector part of the instrumentation is

surrounded by protective materials, or active protection elements are used by means of hooking up combined detector assembles in "coincidence" or "anticoincidence" modes. In addition, in order to reduce the influence of medium background, use is made of coordinate-sensitive methods of recording the γ-field using detectors assembled in the form of matrices with a coded aperture (γ-telescope). Such instruments can be used for detecting and locating γ-radiation from a nuclear weapon on sea and land carriers.

In order to optimize the "quality factor" of a detector using the S(E) parameter, the most effective approach is to use detectors with an extended surface, i.e., detector assemblies of individual sensing elements based on NaI or CsI or other materials. Such assemblies were included in the γ-spectrometers of the "Sever" and "Agat" types developed by the Institute of Geochemistry and Analytical Chemistry, USSR Academy of Sciences, for the detection of sea-launched nuclear weapons.

Operating Principle of γ-Spectrometer Packages

The "Sever" γ-spectrometer package is intended for the detection and identification of nuclear weapons carried aboard ships. It includes two independent channels: a remote γ-spectrometer with a directional effect with a total area 0.25 m (8 NaI-based detectors) and a remote γ-spectrometer for measuring and analyzing data by the contact method. Its operating principle is based on having the flux of γ-quanta of different energies be recorded by the sensing elements of the detector assembly. Upon entering into the body of the scintillation detector, the γ-quanta interact with atoms of the scintillation material, which is capable of transforming the energy of a γ-quantum into light pulses with amplitudes proportional to the energy of the γ-quanta. The light pulses are transformed in a photomultiplier (PM) into an electrical signal and are amplified. The pulses of different amplitudes fed from the PM output, after passing through amplifiers, are sent to the input of an amplitude analyzer where they are sorted by amplitude. Depending on the number of channels in the analyzer (from 128 to 1024 or more), pulses of certain amplitudes are recorded channel by channel in accordance with the amplitude of the pulse recorded in the detector. At the analyzer output we obtain an instrument spectrum which is calibrated from sources of γ-radiation (for example, ^{137}Cs with $E_\gamma = 667$ kev or ^{60}Co with $E_\gamma = 1.17$ and 1.33 MeV). A calibration curve is plotted using the positions of the maxima of the photopeaks of certain energies in certain analyzer channels. This curve can be used in determining the energy of a recorded γ-quantum or in constructing the full energy spectrum of the flux of γ-quanta entering the detector. The programs implemented in the "Sever" package make it possible to perform simultaneous continuous collection and processing of data from remote and contact sensors on a real-time basis.

The response of the remote channel of the "Sever" package in the 0.1-1.3 MeV range (from a ^{60}Co point source) is 1.3×10^{-5} pulses/photon and 1.3×10^{-6} pulses/photon at distances 50 and 100 m from the source, respectively. With a

known background level it is also possible to estimate the threshold response of the "Sever" package for a specific situation.

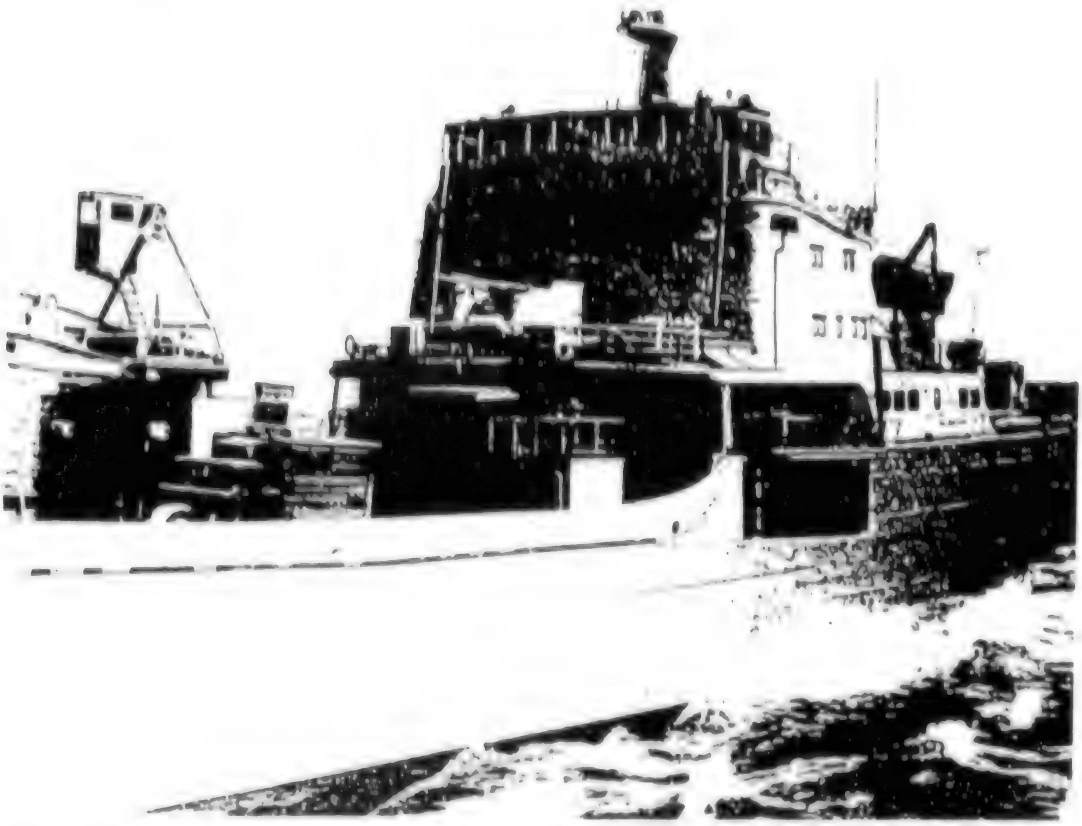
The 'Agat" γ-telescope is intended for the detection and determination of the location and spatial distribution of nuclear weapons on ships. In its development, use was made of a coordinate-sensitive method for recording γ-quanta by a detector assembly in the form of matrices with a coded aperture, making it possible to discriminate point sources against the background of the ambient medium.

The operating principle of the "Agat" telescope involves the following. The flux of γ-quanta recorded by a detector matrix passes through a special mask, which constitutes a unit with open and closed elements in a given sequence. This makes it possible to modulate the flux of γ-quanta incident on the detector mask in conformity to a selected law for the coding aperture, which is mounted in front of the coordinate-sensitive matrix (CSM) at a distance ensuring an angle of view of 15-34° and an angular resolution 4°. The signals from the PM outputs, which do not coincide in time with the signals of the active shielding unit, are fed to the inputs of the data recording and processing units in which the linear filtering, processing, and retrieval of the image of the γ-field, recorded by the CSM on a real-time basis, are performed. Next the retrieved image in the form of a matrix of intensity of the γ-field is reproduced on a display screen. A television camera whose optical axis is matched with the optical axis of the CSM was used for referencing the spatial distribution of the γ-field to the target investigated with the telescope. This makes it possible to see the position of the detected sources of the γ-field on the ship under observation. With a total detector assembly area 440 cm^2, the response of the γ-telescope is (1-6) x 10^{-2} (pulses/photon) in the range 0.1-1.3 MeV.

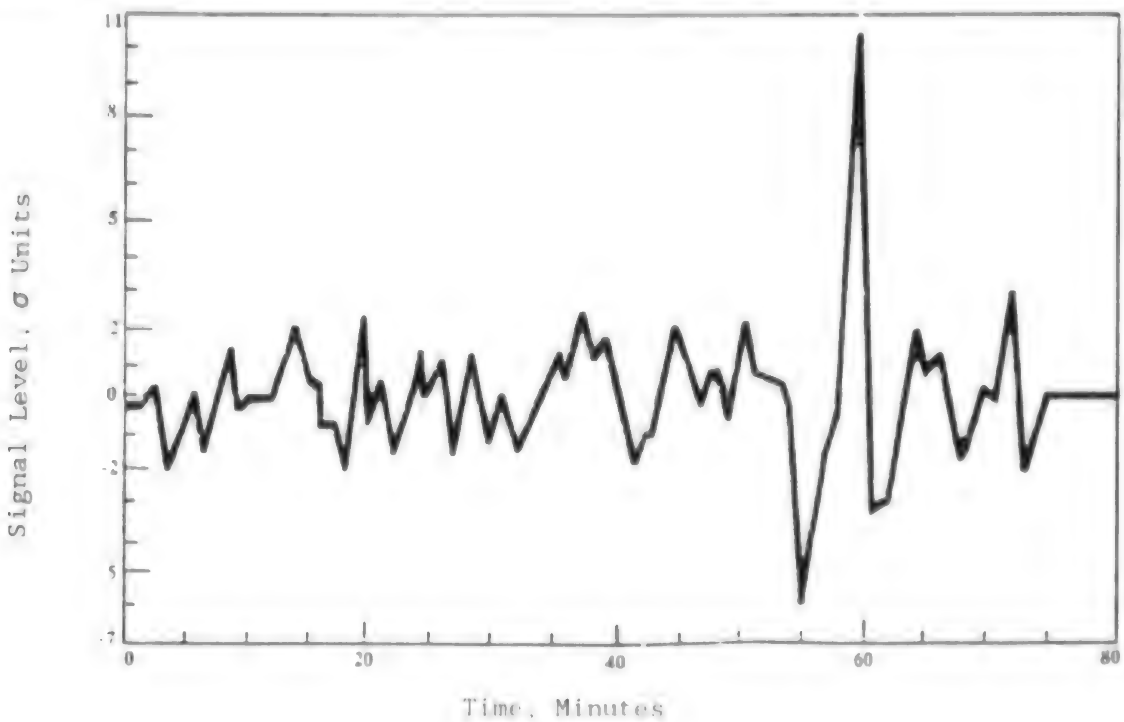
The "Sever" and "Agat" packages represented the contribution of the Institute of Geochemistry and Analytical Chemistry, USSR Academy of Sciences, to the Soviet-American experiment in the Black Sea. In addition, the following were used in the experiment: the "Rosa" package (developed by the Earth Physics Institute imeni O. Yu. Shmidt, USSR Academy of Sciences) with a semiconductor contact detector, the "Sovetnik" package (developed by the Atomic Energy Institute imeni I. V. Kurchatov), intended for detecting nuclear weapons from a helicopter on the basis of neutron radiation, and an American package of contact apparatus based on semiconductor detectors.

Results of Black Sea Experiment

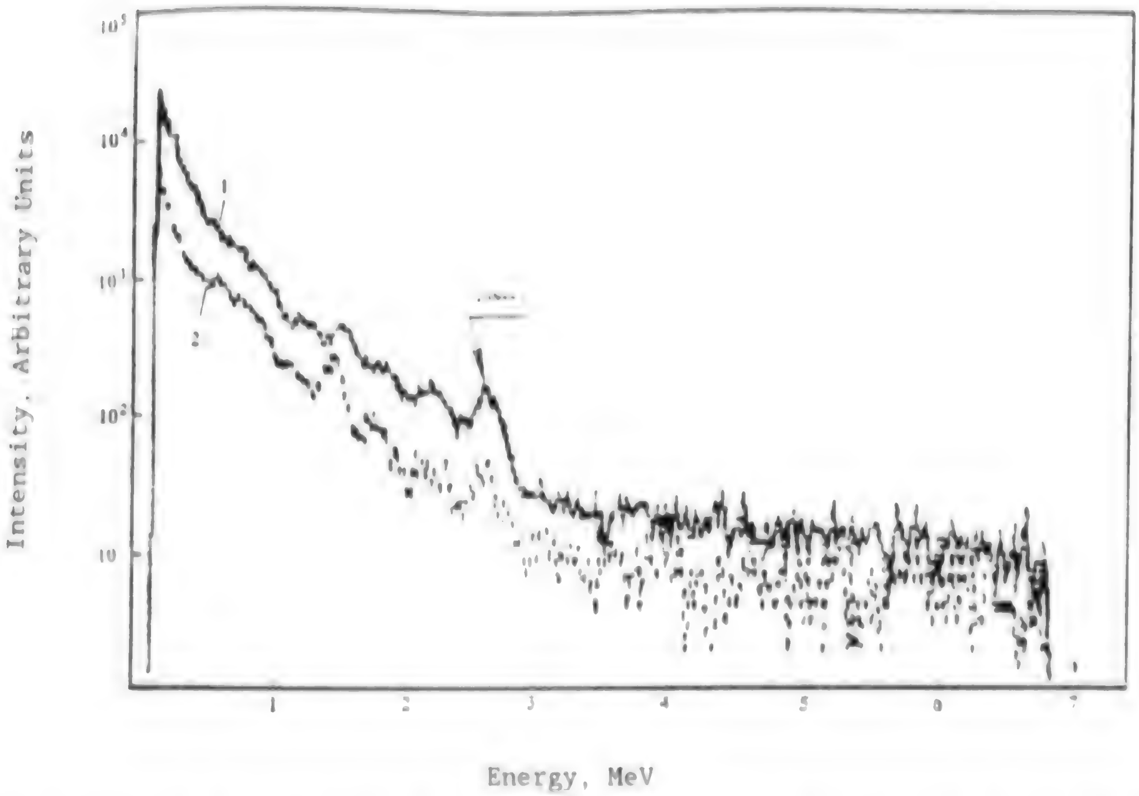
To conduct the first Soviet-American experiment, representatives of the USSR Navy assigned the missile cruiser "Slava," equipped with a sea-launched cruise missile (SLCM) of the series SS-N-12 with a nuclear weapon, a large landing ship with the "Sever" package, and the auxiliary ship "Apsheron" with a "Sovetnik" helicopter package, as well as the ship "Yenisey" for the participants in the experiment.



"Sever" package on large landing ship (Yalta, 5 July 1989).
It is intended for the remote and contact detection and monitoring of nuclear weapons on ships.

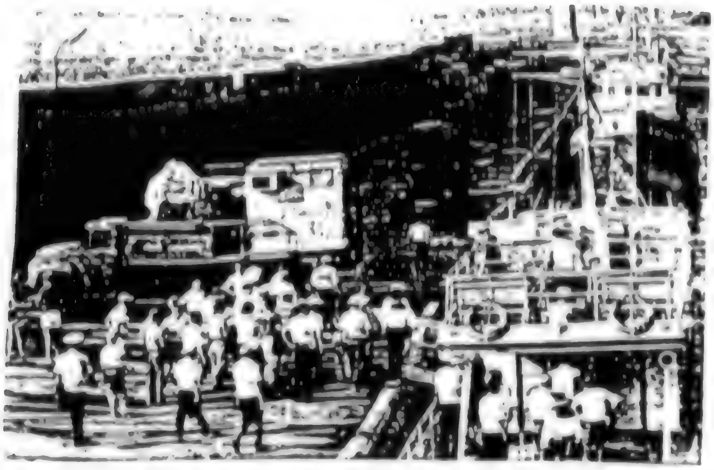


Anomaly of γ-field detected by "Sever" package on cross-piece of cruise missile launcher on cruiser "Slava" (range 50 m), evidence of presence of source of γ-radiation there (the measurements were made in the 0.2-0.8 MeV range).

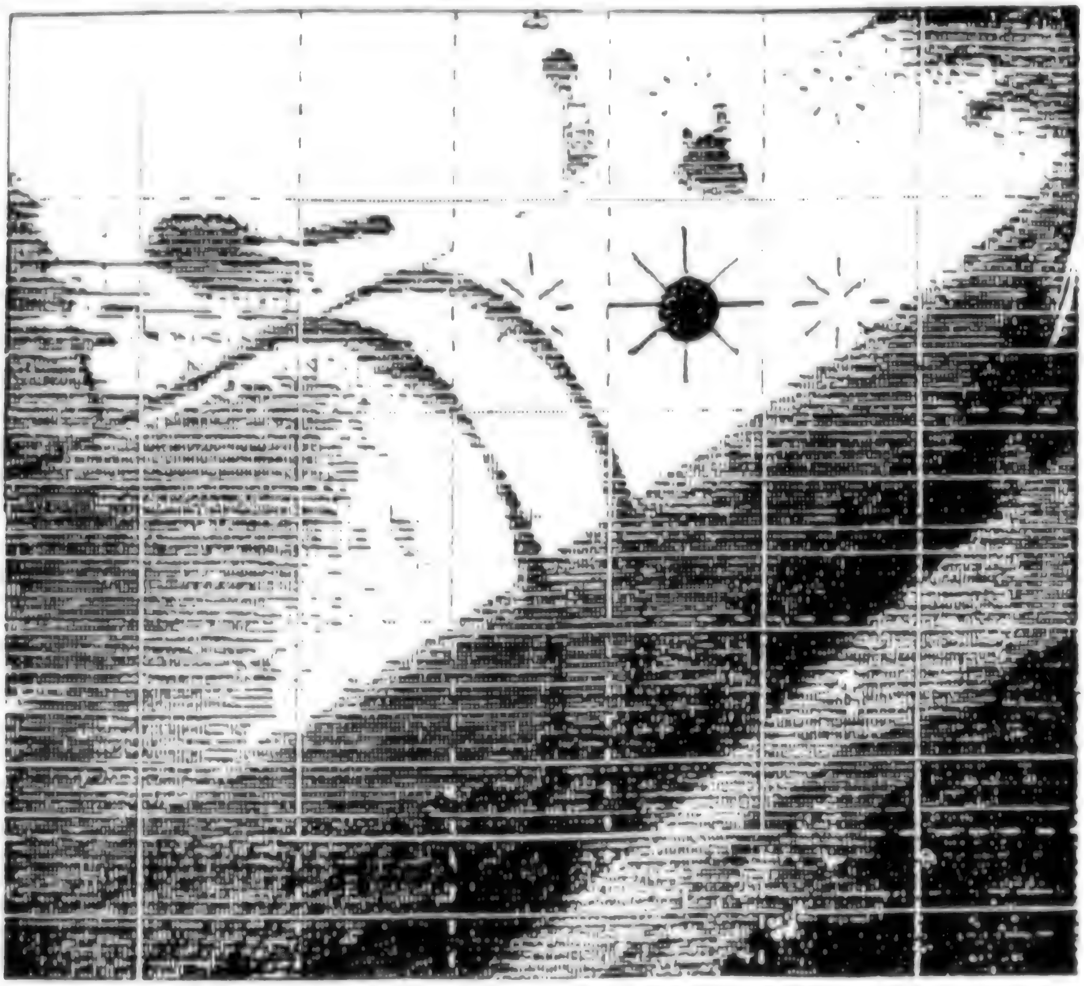


Gamma-spectrum (1) recorded by contact sensor. The photopeak in the 2.62 MeV region and presence of hard γ-radiation in the 3-6 MeV region indicate the presence of a nuclear weapon in a cruise missile (2 -- background spectrum).

The "Slava" missile cruiser carried all the contact instrument packages supplied by the USSR and the United States. The leaders of the USSR Navy allowed research directly with a SLCM with a nuclear weapon. The landing ship with the "Sever" package was used for remote measurements of the γ-field from the nuclear weapon carried aboard the cruiser "Slava" with the ship a distance stationed up to 60 m away. It was demonstrated on the basis of these measurements that γ-field anomalies from the nuclear weapon were reliably detected at distances up to 50-60 m from the cruiser "Slava" by the "Sever" package on the cross-piece of the SLCM launcher.



"Agat" package placed on truck, intended for detecting and determining location of nuclear weapon on ship at dockside.



Spatial image of γ-field recorded by coordinate-sensitive mask of package which shows the location of a nuclear weapon in cruise missile launcher (printout from computer screen of "Agat" package).

When the "Slava" was at dockside, research was carried out for determining the spatial structure of the γ-field near the launcher of the SLCM with a nuclear weapon; the flux of γ-quanta was measured at the launcher surface. In addition, the "Agat" γ-telescope, which is designed for detecting and determining the locations of the sources of γ-radiation aboard ships standing at dockside, was tested. The results of this research revealed that the distribution of the γ-field at the surface of the launcher of a SLCM with a nuclear weapon is anisotropic, and this is obviously related to the design features of nuclear weapon placement and the use of materials with different properties of absorption and scattering of γ-quanta. The total flux at the launcher surface was $1\text{-}3 \times 10^6$ 1/s, which is consistent with the theoretical estimates. The results of tests of the "Agat" γ-telescope revealed its good suitability for use in detecting and determining the locations of nuclear weapons on ships at dockside. At a distance 10-12 m from a ship, the "Agat" γ-telescope not only detects a nuclear weapon, but also the point where it is located in the sea-launched cruise missile. The principles for detecting, pinpointing and spatial determination of the positioning of sources of γ-radiation worked out in this experiment were used in developing the new "Ametist" γ-telescope with improved response and better spatial resolution for solving problems related not only to the detection and locating of sources of γ-radiation, but also the possibility (when there are two or more nuclear weapons aboard a ship) of distinguishing them in space. Tests of this package, as well as a new shipboard package with a detector assembly with an area 1.5 m^2, will be carried out this year.

Outlook

The results of the Soviet-American experiment indicated that the methods and apparatus proposed by Soviet and American scientists can be used effectively in organizing a system for monitoring sea-launched nuclear weapons on the basis of γ- and neutron fields, as being the best-studied at the present time. However, if a nuclear weapon is considered as a potential source of other fields, in addition to nuclear radiation the energy of the fissionable materials can also be transformed into other types of radiation resulting in the formation of anomalies, for example, in thermal, electromagnetic, optical and other fields. Here, too, it is necessary to carry out a number of theoretical and experimental studies for detecting new informational criteria on whose basis it is possible to detect and identify the presence of nuclear weapons on ship carriers. The broadening of our concepts concerning the physical fields of disturbances created by nuclear weapons will afford us the ability to optimize remote-contact methods and equipment for monitoring nuclear weapons on ship carriers. With such equipment available, it also will be possible to work out further the concept of the mechanism of monitoring of sea-based nuclear weapons. This must done with allowance for the tactical-technical characteristics of systems of nuclear weapons and the conditions for their installation on warships and transport ships. Monitoring for the presence of nuclear weapons on surface carrier ships can be done on the surface of the world ocean and in ports where they are based in two

stages. In the first stage sources of γ- and neutron radiation are detected on the ship to be inspected remotely from a distance 50-200 m (from a ship or from a helicopter which carries the instrument packages for the detection of nuclear weapons). The nuclear weapon is identified in the second stage. A transfer capsule with a self-contained γ-spectrometer that is equipped with a telemetric connection to a control post situated on a ship or on shore is conveyed to the side of the ship to be checked out. On command from a controller, the capsule is put into positions for the detection of anomalies of γ- or neutron fields. All the information from the γ-spectrometer, together with a television image of the site where the capsule is positioned, is transmitted to the control post for subsequent processing and for classifying the anomaly detected by the remote apparatus.

In our opinion, the development of an integrated remote-contact package will make it possible to design a mutually acceptable, highly reliable monitoring system capable of executing the necessary measures for checking for the presence of nuclear weapons on ships in different seas and oceans with adherence to national and international juridical norms.

In conclusion, it must be noted that the equipment for the checking for of sea-launched nuclear weapons can be used successfully both for monitoring the production of fissionable materials used in nuclear weapons and in areas where they are stored and transported to ports where ships carrying nuclear weapons are based.

Note From Editor

Work on the detection of nuclear weapons aboard surface and underwater transports has been done over the decades at the Atomic Energy Institute imeni I. V. Kurchatov in collaboration with the USSR Navy, Helicopter Design Bureau imeni N. I. Kamov and a number of other organizations. During 1987 a USSR State Prize was awarded for this work. The editors hope to return again to the history of this research and discuss in greater detail the instrument packages developed with the participation of the Atomic Energy Institute imeni I. V. Kurchatov. [Editorial note signed by L. P. Feoktistov, corresponding member USSR Academy of Sciences, Deputy Chief Editor of the journal PRIRODA.]

Footnotes

1. Gsponer, A. "La bombe a neutrons," LA RECHERCHE, Vol 15, No 158, pp 1128-1138, 1984.

2. Zans, L. "Statisticheskoye otsenivaniye" (Statistical Evaluation), Moscow, Statistika, 1976.

In the Energy Active Region of the Ocean

907N0161 Moscow ZEMLYA I VSELENNAYA in Russian No 4, Jul-Aug 90 pp 59-64

[Article by R. V. Ozmidov, Doctor of Physical and Mathematical Sciences, USSR Academy of Sciences P. P. Shirshov Institute of Oceanology.

[Text]

Course--To the Gulf Stream Current

It is winter 1988. Preparations are being made for the 48th voyage of the scientific research ship Akademik Kurchatov, bound for Newfoundland off the Canadian coast.

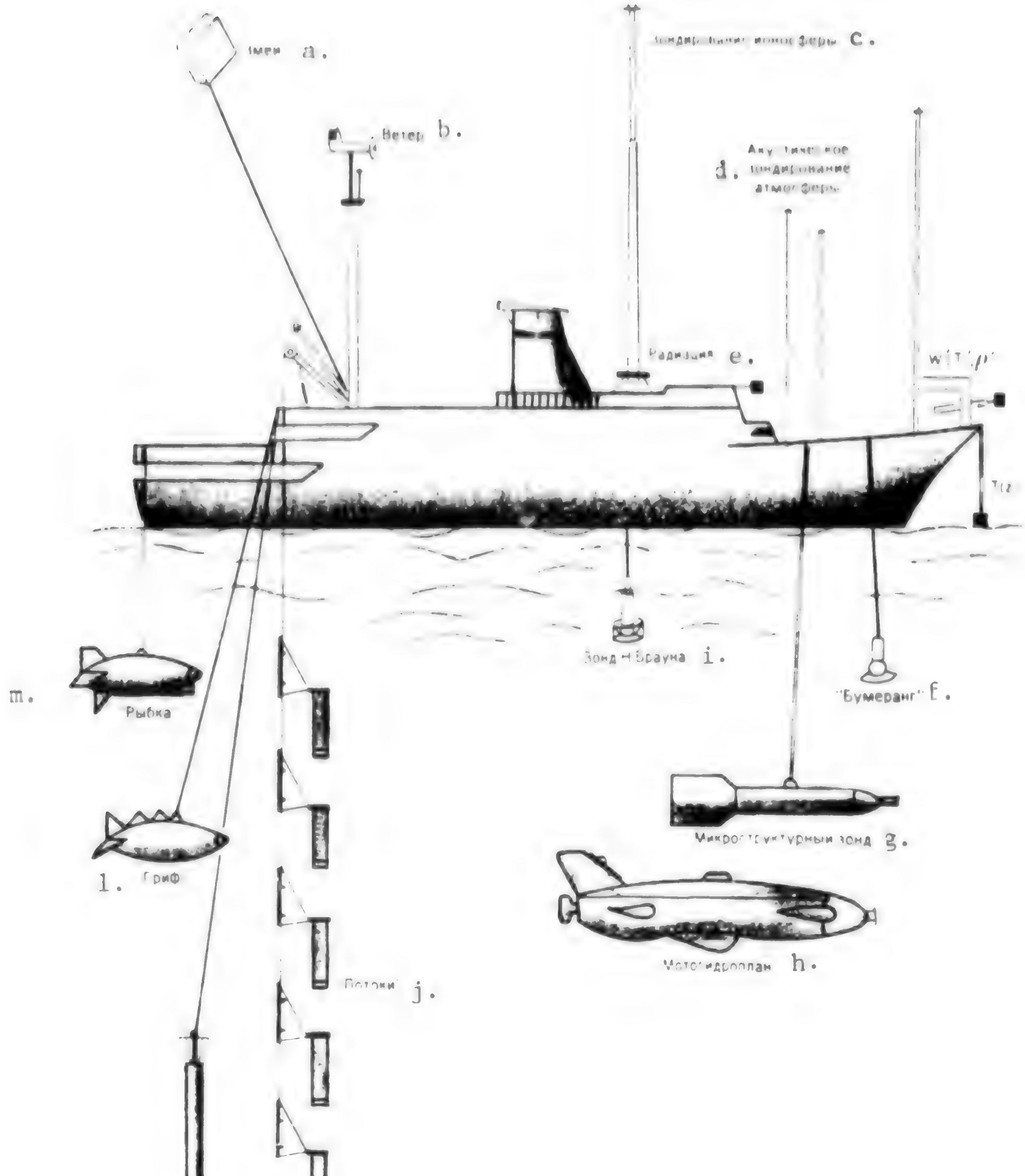
Why are Soviet oceanologists interested in this region of the Atlantic, which is so far from our country? Natural processes occurring in the ocean and atmosphere there have a direct relation to weather and climate in the Soviet Union, not only in the European region, but also in some of the Asian region. In the Newfoundland region, the warm waters of the Gulf Stream, which is called the North Atlantic Current here, meet the cold streams of the Labrador Current and, as they mix, form zones with large drops in temperature. Due to the active heating of the air in some regions, and cooling in others, cyclones are rapidly formed which then move to the east toward Europe. Carrying their enormous supplies of heat and moisture to Europe, they form weather and climate conditions over vast territories.

It is clear that the possibility of predicting weather and climate on the European continent depends significantly on our knowledge of the Gulf Stream and its variability, on the mechanisms of heat and moisture transfer from the ocean to the atmosphere, and on their dynamic interactions. All of these, unfortunately, have been insufficiently studied, because in the Newfoundland region of the Atlantic, where storms are commonplace, it is difficult to make observations.

A study of the structure and variability of hydrophysical fields in the Newfoundland test site, one of the energy active regions of the world ocean, a study of the atmosphere above the test site, and determination of the basic parameters of the interaction of the air and water are the tasks of the expedition on the Akademik Kurchatov.

Equipping the Expedition

The ship has equipment to measure the average and pulse (turbulent) characteristics of hydrophysical and meteorological fields. The properties of ocean fields on the



Equipment complex of the 48th voyage of the scientific research ship Akademik Kurchatov. a. kite; b. wind; c. ionosphere probe; d. acoustic sounding of atmosphere; e. radiation; f. Boomerang; g. microstructure probe; h. Motogidroplan; i. N. Braun probe; j. Potok probes; k. Baklan; l. Grif; m. Rybka.

scale of the entire test site are studied by the Potok [flow] current measurement devices, which are either installed on buoys or submerged off the ship. Measurements are also made by hydrological probes from the N. Braun company. These devices make it possible to determine with great accuracy the temperature, salinity, and density of ocean water. These instruments work in sounding mode (to a depth of 2000 m) from a drifting ship, and scanning mode (to 500-600 m) on a small course of the ship. To scan, the probe was placed in a streamlined body, the Rybka [small fish], which made it possible to submerge the instrument to a lower depth.

Measurement of the small scale pulsations of hydrophysical fields were made during the expedition by the Baklan probe, which has sensors for pulsations in temperature, the electrical conductivity of the water, and pulsations in the current velocity. There are also sensors for water pressure and the acceleration of the probe. The Baklan is submerged on a thin cable, and after a full sounding cycle at 400 m, which usually takes 35-40 minutes, it is raised. Signals enter a computer from the probe's cable. Preliminary processing is done in the computer.

The pulsation hydrophysical characteristics in the uppermost layer of the ocean were measured with the Boomerang probe, which has sensors for temperature, electrical conductivity, and pressure, analogous to the sensors of the Baklan probe. After it is lowered from the ship, the Boomerang remains afloat until water fills its float chamber, then it began to sink. This device of the probe made it possible to measure the surface layer of the water, beginning from very small depths, a total of several centimeters.

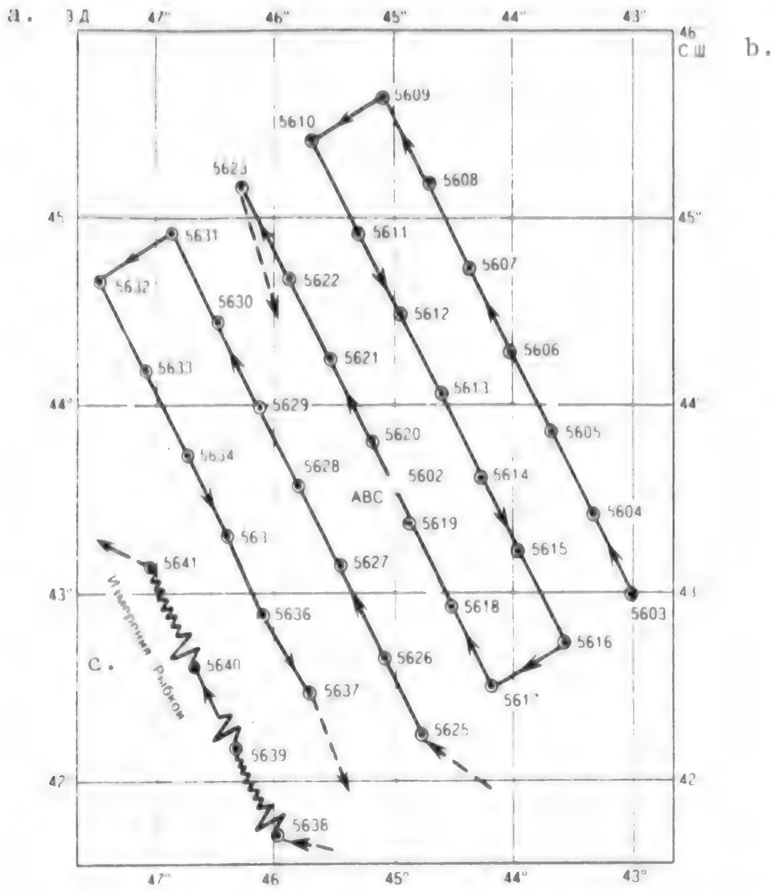
To measure the turbulent fluctuations in towing mode the Grif probe is used, which measures turbulence. It has the same complement of sensors as the Baklan probe. When the Grif probe is towed it is lowered from the ship by a special device on a stabilizer and is towed on a cable.

A study of the fine structure of the velocity field of currents is done using a microstructure probe which is equipped with a miniature propeller to measure the velocity of the movement of the water relative to the probe. It also has a temperature sensor. In this probe the velocity of the current is averaged over each meter of submersion (the maximum submersion of the probe is 2000 m), which made it possible to obtain almost continuous profiles of the velocity of the current relative to the probe. The absolute values of the velocity are added from the measured values and the vectors of the drift velocity of the ship.

During the voyage a new autonomous hydrophysical measurement complex was tested, the Motogidroplan. The instrument is not connected to the ship by a cable. All the information from the sensors (which are analogous to the Baklan sensors) are recorded by a device inside the probe. Engines, fins, and a rudder are used to control the craft, which may submerge to a depth of 250 m.

The work of the voyage successfully combined hydrophysical measurements with the study of the atmosphere above the ocean. In the surface layer of atmosphere, pulsation measurements were made which made it possible to directly calculate the fluxes of the momentum, heat, and moisture in the interaction of the ocean and atmosphere.

For standard meteorological observations (which are made hourly at the research site) the following instruments were used: psychrometer, aneroid barometer, anemometer, thermometer. Pulsation measurements of the components of wind



Cross sections (bold lines with arrows) and stations (denoted by numbers) at the Newfoundland test site. At the center of the test site is the autonomous buoy station (ABC). At the stations measurements are made by the N. Braun and Baklan probes, and pulsation measurements are made in the surface layer of atmosphere (shown by colored arrows). The scanning measurements of the Rybka probe are made in the sixth cross section of the test site to depths of 1500 and 600 m.
a. west longitude; b. north latitude; c. Rybka measurements.

velocity, temperature, and humidity were made by acoustic anemometers, pulsation resistance thermometers, and an infrared optical hydrometer. All of these sensors are arranged on a special rod, a boom, in the nose of the ship. Hydraulic control made it possible to change the extension of the boom and the height of the instruments above sea level. Especially valuable measurements from the boom were simultaneous recordings of the pulsations in the vertical component of air velocity, w', pulsations in temperature T', and humidity ρ'. The derivative $w' \cdot T'$ (or $w' \cdot \rho'$) defines the vertical flux of heat (moisture) in the surface layer of atmosphere above the ocean, which is the most important parameter of the interaction of the ocean and the atmosphere.

To study the processes of interaction of the ocean and atmosphere it is very important to know the components of the radiation balance in the surface layer of atmosphere. The following instruments were used during the voyage for these measurements: a thermoelectric actinometer (flux of direct solar radiation), pyranometer (fluxes of total and reflected radiation), balansometer (longwave radiation balance), pyrgeometer (longwave radiation of the atmosphere and ocean).

The sensors for the measurement of the radiation fluxes were attached by Cardan joints to a 7-meter boom installed on the bridge of the ship. The sensors operated around the clock, and the collected information was recorded by a multi-channel automatic recorder.

During the expedition, observations were also made of atmospheric aerosols, which play an important role in the thermal balance of the ocean and atmosphere. These studies were done using a optical counter with a 16-channel pulse analyzer and a digital printer (the counter recorded particles with radii of 0.2-5.0 μm). Also used was a photoelectric aerosol nephelometer to measure the coefficient of directed light scattering.

The structure of the boundary layer of the atmosphere above the ocean was studied using remote methods, acoustic sounding with a three-component Doppler acoustic locator. The principle of the locator is based on the reflection of a powerful directed beam of acoustic energy by structural inhomogeneities of the atmosphere. The beam is radiated by a parabolic antenna. The data make it possible to judge the distribution and intensity of turbulent layers in the atmosphere, the characteristics of temperature fluctuation, and components of the wind velocity vector at altitudes from 40 to 500 m. To determine the humidity of the air at 300-400 m a radiopsychrometer was used that was raised on a balloon or a kite. Information from the instrument was transmitted to the ship by a radio channel.

The parameters of the ionosphere above the region were determined by an autonomous ionospheric station.

At the Newfoundland Test Site

Work at the test site began on March 3, 1988 with the installation of the buoy station with Potok current measurement devices. The buoy was placed in the center of the test site, which consisted of six cross sections across the front of the Gulf Stream, with seven comprehensive hydrometeorological stations in each cross section. The distance between stations (there were about forty) and the cross sections was 30 miles. It was planned to use the N. Braun probes at the stations to make measurements to depths of 2000 m. The Baklan probe would be used to make measurements to a depth of 300-400 m. This made it possible to obtain information on the large-scale structure of the hydrophysical fields in this region of the Atlantic, as well as information on the fine structure of the fields and turbulence. Between some of the stations (through about one) there were plans to make pulsation measurements in the atmosphere for a small ship course.

Work at the test site had to be conducted in complex weather conditions. Sometimes the wind intensified to storm winds. This forced an interruption of measurements until the wind abated somewhat. Nonetheless, by March 14 all stations were completed to the last one in the fifth cross section. Then the weather grew much worse, a storm which registered a 9. On March 19, when the wind abated somewhat, the decision was made to complete the sixth cross section of the test site using the towed Rybka probes. With great difficulty (due to the large swells) the Rybka was lowered from the ship and began making measurements. At the beginning of this cross section (the last in the test site) the sounding depth of the Rybka reached 1500 m, then scanning was done to a depth of 500-600 m. Two series of pulsation measurements were also made in this cross section in the surface layer of the ocean, and on March 23 work at the test site was concluded.

Scientific Results

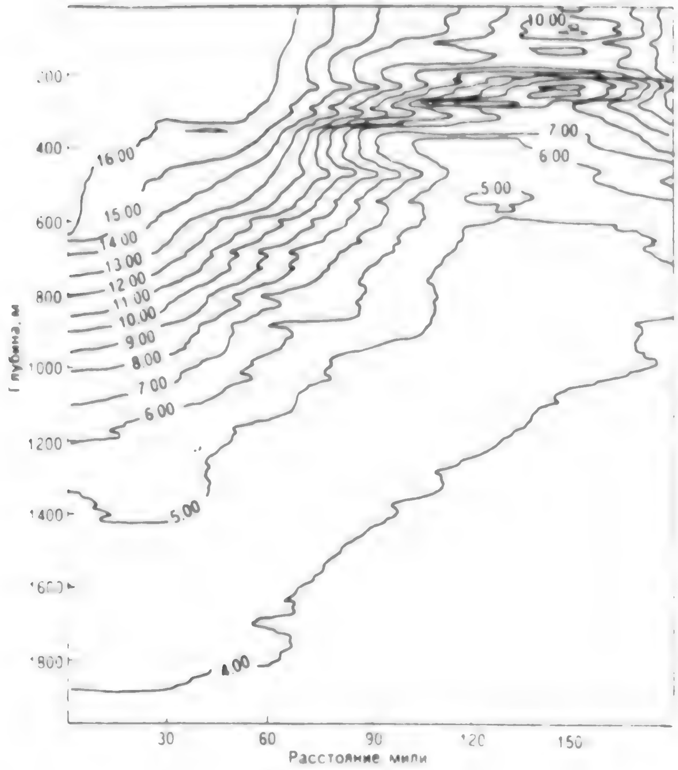
An important result of the measurements made at the Newfoundland test site is the determination of the components of the thermal balance of the surface of the ocean. It was found that the average influx of heat due to solar radiation is 100 W/m^2 of ocean surface. However, due to longwave radiation the ocean loses 40 W/m^2. Due to turbulent heat exchange and the exchange of moisture between the ocean and atmosphere the heat flux varies from 200-1400 W/m^2. This variability of the components of the thermal balance is due to their strong dependence on drops in temperature between the ocean water and the air, on the humidity of the air, and the wind velocity. The difference in the temperatures of the water and air varied over the time of work at the test site from +13°C (water warmer than the air) to negative values (when the air was warmer than the water). The wind velocity varied from moderate winds to storm winds.

This wide range of conditions made it possible to make a conclusion which has great practical significance. Usually, in calculations of heat exchange between the ocean and atmosphere, the weather services of all countries use semi-empirical formulas to determine the heat fluxes. These formulas proceed from the data of standard hydrometeorological measurements. When we compare the results of these calculations with direct (pulsation) measurements made on our voyage, it was found that the semi-empirical formulas used in mass calculations yield substantial errors for extreme values of observed parameters, that is, storm winds and large drops in temperature between the air and water. If one considers that the heat exchange increases significantly, then even small corrections to the results of calculations may have a substantial effect on conclusions regarding the effect of the ocean on weather and climatic processes.

Interesting results were obtained in the expedition during the study of aerosols. The sizes of aerosol particles over the ocean were determined, and it was shown that there is a dependence of the concentration of aerosols on the intensity of waves. Consequently, these particles are generated by spray, and broken up by the crests of waves during strong winds. Aerosol, which changes the optical properties of the atmosphere, affects the influx of solar energy to the ocean and thus its thermal and dynamic characteristics.

The basic property of the hydrological structure of water in the Newfoundland test site is the strong stream of the North Atlantic Current, which is separated from the cold waters of the Labrador Current by a clear frontal zone. The drop in water temperatures at the front reach 17°C(!). The frontal zone has a complex structure: cold and warm waters mutually penetrate each other forming separate "tongues," meanders, and eddies.

Measurements of the Braun probe made it possible to determine the characteristics of the fine structure of hydrological fields in the test site. The average values of the thickness of the inversion and homogeneous layers of water were calculated. The great number of these layers indicates the dynamic activity of water and the complexity of their mixing mechanisms. It was found that the interstratification of the water increases in the frontal zone, and it is here that the number of inversion layers increases. The interstratification of the water is linked with the intensity of the mixing processes: in individual layers tens of meters thick, the intensity of mixing may be significantly larger than in neighboring layers.



Vertical cross section of the water temperature field through the frontal zone of the North Atlantic Current and the Labrador Current (numbers on the isotherms indicate temperature in degrees Celsius). The sharp drop in temperature across the front, from 16°C to 5°C is characteristic for this region of the Atlantic. X-axis: Distance, miles; Y-axis: Depth, m.

Turbulence and the mixing processes are maximal in the frontal zone. In storm conditions the entire 200-meter upper layer of the water becomes strongly turbulent. At greater depths, where the storm has almost no effect, no more than 5 percent of the water layers are turbulent. Preliminary analysis of the data showed that the distance between turbulent layers, their thickness, and the distance between groups of layers may be described by some theoretical expressions. These provide a basis for predicting the characteristics of turbulence, and consequently, make it possible to calculate the fluxes of heat, salt, momentum, and other properties of the ocean depths.

Preliminary results make it possible to conclude that the work of the Akademik Kurchatov substantially advanced the study of the complex processes of the formation of the structure and interaction of the ocean and atmosphere in the energy active region of the ocean near Newfoundland. The scientific results which were obtained will help us to better understand the processes which occur there and will make it possible to improve methods of calculating them.

Soviet and American oceanologists on board the Akademik Kurchatov in New York Harbor. The second from the right is Professor M. Bauman, the fourth from the right, Professor R. V. Ozmidov.

Meetings with American Oceanologists

After it left the stormy region of the North Atlantic, the Akademik Kurchatov spent several days in New York. One day the ship was visited by a group of American oceanologists headed by the director of the Center of Marine Research of New York University, Professor M. Bauman. The guests became acquainted with the work done during the voyage, and were shown the scientific equipment of the ship. On the following day, we visited the Center, which was about 100 km from New York in a forested region of Long Island. The main direction of research conducted at the center is all aspects of coastal oceanology (physical, chemical, geological, and biological). The center is also concerned with the fishing industry, aquaculture, and the problems of ocean pollution. Famous scientists work there: Professor A. Okubo, a specialist in the diffusion of pollutants in the ocean; Professor H. Carter, and D. Prichard, specialists in the processes of exchange and currents in estuaries; Professor J. Shubel, who studies oceanological sediments; and Professor P. Bail, a specialist in physical oceanology. Professor Bail's book "Popular Oceanography" is well known in our country.

About one hundred students and graduate students (many from Asian countries) study and are trained at the Center for Marine Research. The laboratories of the center are well equipped with measurement devices, computers, and other equipment. The computers at the computing center have color displays, laser printers, and plotters. The Center has a small research ship for coastal sailing. It was here that the Soviet-American colloquium on urgent problems in oceanology was held.

A famous specialist in ocean turbulence, Professor K. Gibson of the Scripps Oceanographic Institute (California) came to the center to meet the Soviet oceanologists on the Akademik Kurchatov. He gave an interesting lecture on the latest studies in ocean turbulence. M. Bauman and K. Gibson expressed their interest in strengthening contacts between the oceanologists of the USSR and USA to conduct joint research and ocean expeditions. At present these hopes have materialized in specific agreements and are being successfully brought to life.

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Effect of Turbulence on Impurity Observation in Upper Atmosphere Using Lidar Method

917N0014A Ashkhabad IZVESTIYA AKADEMII NAUK TURKMENSKOY SSR: SERIYA FIZIKO-TEKHNICHESKIKH, KHIMICHESKIKH I GEOLOGICHESKIKH NAUK in Russian No 5, Sep-Oct 90 (manuscript received 12 Jan 87) pp 18-22

[Article by M.F. Lagutin, D.M. Smagin and A.D. Pivnenko (Kharkov Radioelectronics Institute)]

[Text] The lidar method (optical detection and ranging) of studying the behavior of man-made impurity releases [5] has been widely used in recent years in studies of the upper atmosphere dynamics and parameters. The method is very sensitive, and this significantly affects the impurity observation process, which has long duration, unlike observation methods such as meteor radar, and photography of meteors and man-made glowing clouds.

Our analysis of the space-time behavior of impurity pertains to 80-100 km altitudes (the mesosphere and lower thermosphere) at medium latitudes and applies to the optical detection and ranging method. There is developed turbulence at these altitudes - the Reynolds number is several tens of thousands. We assume that impurity consists of a monocomponent neutral conservative gas and that its diffusion occurs in the uniform stationary turbulence field. We choose a moving coordinate system whose origin coincides with the impurity release point and is moving at the regular wind velocity. Under these conditions the process of impurity diffusion is described in [6] by the following equation of turbulent diffusion:

$$\frac{\partial q}{\partial t} = K_x(t)\frac{\partial^2 q}{\partial x^2} + K_y(t)\frac{\partial^2 q}{\partial y^2} + K_z(t)\frac{\partial^2 q}{\partial z^2}, \qquad (1)$$

where q is impurity concentration, x is the coordinate in the West-East direction (zonal coordinate), y is the coordinate in the South-North direction (meridional coordinate), z is the coordinate in the vertical direction, and $K_x(t)$, $K_y(t)$ and $K_z(t)$ are time-dependent turbulent diffusivities along directions x, y and z, respectively. The solution of equation (1) makes it possible to describe the behavior of impurity concentration field q(x,y,z,t). The form of the solution is determined by the law of time dependence of turbulent diffusivities. For a free unlimited space in the presence of an instantaneous point source the solution of equation (1) is

$$q(x, y, z, t) = \frac{Q}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} \exp\left\{-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right)\right\}, \qquad (2)$$

where Q is the amount of impurity, and $\sigma_x^2, \sigma_y^2, \sigma_z^2$ are time-dependent impurity concentration variances along directions x, y and z, respectively. Expression (2) is the canonical form of normal distribution in a three-dimensional space. In the case of statistical interpretation of the process of turbulent diffusion of impurity, turbulent diffusivities and variances are related as follows [6]:

$$K(t) = \frac{1}{2}\frac{d\sigma^2(t)}{dt}. \qquad (3)$$

We shall be interested in cloud dimensions within which impurity concentration does not fall below a certain minimum level q_{min} that depends on sensitivity of the lidar system equipment. According to (2), impurity particles with density $q(x,y,z,t) \geqslant q_{min}$ form an ellipsoidal cloud

$$\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z} = m^2. \qquad (4)$$

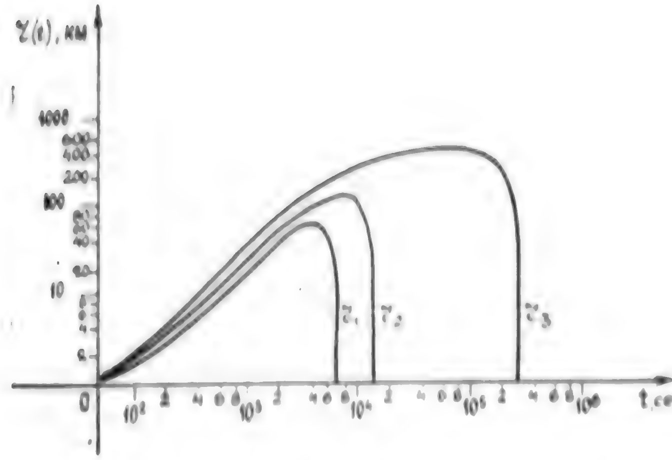
Semiaxes a, b and c of ellipsoid (4), which characterize dimensions of a visible cloud, are proportional to standard deviations $\sigma_x, \sigma_y, \sigma_z$: $a = m \cdot \sigma_x$, $b = m \cdot \sigma_y$, $c = m \cdot \sigma_z$ (m is the proportionality factor). The projection of ellipsoid (4) on a horizontal Earth plane is the area of the ellipse within boundaries of which impurity will be detected during vertical sounding. The area dimensions correspond to dimensions of ellipsoid (4) cross-section by a central horizontal plane (z = 0). We shall examine in great detail the case of isotropic impurity diffusion in a horizontal direction, when $\sigma_x = \sigma_y$. In this case one can easily derive from expression (2) the time dependence of radius r(t) of the central horizontal diffusion circle. Introducing notation $r(t) = (x^2 + y^2)^{1/2}$ and equating expression (2) to q_{min}, which is equal to the observation method sensitivity, we derive after obvious transformations that

$$r(t) = \left[-2\sigma_x^2 \ln\left\{\frac{q_{min}}{Q}(2\pi)^{3/2}\sigma_x^2\sigma_z\right\}\right]^{1/2}. \qquad (5)$$

Time-dependent parameters σ_x^2, σ_z are characterized by different laws at different stages of cloud development.

When studying impurity distribution in a turbulent medium using a statistical method [1, 3, 6], one must consider the following ranges of dissipation of turbulent energy of inertial and large-scale eddies. Diffusion (dimensional increase) of an impurity cloud mainly occurs due to the effect of eddies with dimensions comparable to the cloud dimensions. Our analysis shows that the determining effect of turbulent eddies in the dissipation range is limited by time equal to 77 s, while for inertial range eddies the time limit is 641 s.

Turbulent diffusivities depend on cloud dimensions and hence on time at which the dimensions exceed the external turbulence scale. Based on data on the magnitude of the external turbulence scale [2, 4, 7, 8], the maximum value of



Time Dependence r(t) of Central Radius of Impurity Diffusion Circle

Key:
1. s

horizontal turbulent diffusivity $K_{ox} = 5 \times 10^9$ $cm^2 \times s^{-1}$. The maximum value of vertical turbulent diffusivity K_o is several orders of magnitude lower and is equal to 10^7 $cm^2 \times s^{-1}$. The calculations were performed using the procedure in [7 and 8]. The moment in time when $K_x(t)$ becomes equal to K_{ox} is 3260 s. When cloud dimensions become such that $K_z(t) = K_{oz}$ and $K_x(t) = K_{ox}$, the change in $\sigma^2(t)$ follows the regular molecular diffusion law:

$$\sigma_x^2(t) = \alpha + 2K_{ox}t, \quad \sigma_z^2(t) = \beta + 2K_{oz}t, \tag{6}$$

where α and β are values of $\sigma_x^2(t)$ and $\sigma_z^2(t)$, respectively. Taking into account (6) we derive from (5) the following formula for the horizontal radius of the diffusion circle:

$$r(t) = \left[-2(\alpha + 2K_{ox}t) \ln\left\{ \frac{q_{min}}{Q} (2\pi)^{3/2} (\alpha + 2K_{ox}t)(\beta + 2K_{oz}t)^{1/2} \right\} \right]^{1/2}. \tag{7}$$

We derive impurity concentration in the cloud center (x = 0, y = 0, z = 0) from (2) as follows:

$$q_0(t) = \frac{Q}{(2\pi)^{3/2} (\alpha + 2K_{ox}t)(\beta + 2K_{oz}t)^{1/2}}. \tag{8}$$

The Figure above shows dependences r(t) at $K_{ox} = 5 \times 10^9$ $cm^2 \times s^{-1}$, $K_{oz} = 10^7$ $cm^2 \times s^{-1}$, Q = 10 g, $\alpha = 8.45 \times 10^{12}$ cm^2 and $\beta = 6.12 \times 10^{10}$ cm^2. $r_1(t)$ corresponds to $q_{1min} = 10^3$ cm^{-3}, $r_2(t)$ corresponds to $q_{2min} = 10^2$ cm^{-3} and $r_3(t)$ corresponds to $q_{3min} = 10$ cm^{-3}. The adopted values of q_{1min}, q_{2min} and q_{3min} are equal to sodium, potassium and lithium background noise level, respectively, at concentration maximum altitudes.

The above technique makes it possible to describe the spatial behavior of impurity at any moment in time in fairly great detail. However, for instance, in order to predict an experiment, one needs as, a rule, an approximate estimate of the scale of impurity propagation, with a preliminary analysis of the effect of each of the main parameters (Q, q_{min}, K_{ox} and K_{oz}). We shall now examine the problem of maximum cloud dimensions. Differentiating (7) and equating it to zero, we derive after obvious transformations the following:

$$\frac{q_{min}}{Q}(2\pi)^{3/2}(\alpha+2K_{ox}\tau)(\beta+2K_{oz}\tau)^{1/2}\times$$

$$\times\exp\left\{-\left(1+\frac{K_{oz}(\alpha+2K_{ox}\tau)}{2K_{ox}(\beta+2K_{oz}\tau)}\right)\right\}, \tag{9}$$

where $\tau=t-t_0$.

Lidar systems have very high sensitivity; it is limited by the natural background level and is between 10 and 10^3 cm^{-3}, while the man-made impurity observation time is several tens of hours. Therefore, one can ignore parameters α and β related to the initial period of cloud development. Then from (9) we derive the value of τ at which $r(t)$ has a maximum:

$$\tau_{max}=\frac{1}{4\pi e}\cdot\left(\frac{Q}{q_{min}\cdot K_{ox}\cdot K_{oz}^{1/2}}\right)^{2/3}. \tag{10}$$

The time during which a cloud acquires its maximum dimensions is derived from the following dependence:

$$t_{max}=\tau_{max}+t_0. \tag{11}$$

It follows from (10) that when sensitivity q_{min} or initial mass Q increase by a factor of n, τ_{max} increases by a factor of $n^{2/3}$. Substituting (10) into (7), we derive the following expression for the maximum value of a cloud radius:

$$r_{max}=(6K_{ox}\cdot\tau_{max})^{1/2}. \tag{12}$$

Taking into account (10) we derive from (12) that

$$\frac{r_{2max}}{r_{2max}}=\left(\frac{q_{1max}}{q_{2max}}\right)^{1/3};\ \frac{r_{2max}}{r_{1max}}=\left(\frac{Q_2}{Q_1}\right)^{1/3}. \tag{13}$$

We shall derive maximum impurity observation time τ_{np} from condition $q_0(t) = q_{min}$. Assuming $\alpha=\beta=0$ we derive from (8) that

$$\tau_{np}=\frac{1}{4\pi}\cdot\left(\frac{Q}{q_{min}\cdot K_{ox}\cdot K_{oz}^{1/2}}\right)^{2/3}. \tag{14}$$

We shall derive mean value r_{cp} of a cloud radius by integrating (7) from zero to τ_{np}:

$$r_{cp}=\frac{1}{3}\cdot\left(\frac{Q}{q_{min}}\right)^{1/3}\cdot\left(\frac{K_{ox}}{K_{oz}}\right)^{1/6}. \tag{15}$$

Estimate of Calculation Errors of t_{max}, r_{max} and t_{np}

	t_{max}, c (1)	δt_{max}, %	r_{max}, км	δr_{max}, %	t_{np}, c	δt_{np}, %	q_{min}, $см^{-3}$
Na	4160	2,04	65,21	15,78	6942	2,09	1000
K	8525	1,80	129,24	5,51	18555	0,41	100
Li	93510	0,28	520,62	0,10	249250	0,02	10

Key:
1. s

According to (13), (14) and (15), an n-fold increase in equipment sensitivity q_{min} or initial mass Q increases r_{max} and r_{cp} by a factor of $n^{1/3}$ and τ_{np} by a factor of $n^{2/3}$.

The maximum possible observation time

$$t_{np} = \tau_{np} + t_0. \qquad (16)$$

Calculations demonstrate that the use of approximate dependences (10) and (11) produces a systematic error on the order of $\frac{1}{3} t_0$ in the direction of overestimation, and the use of (14) and (16) results in systematic overestimation of t_{np} by an amount on the order of $\frac{1}{2} t_0$. Based on data derived from calculations of relationships (7) and (8), a comparison was made using a computer. To reduce the error of approximate calculations, one should use the following formulas:

$$t_{max} = \tau_{max} + \frac{2}{3} t_0, \qquad (17)$$

$$t_{np} = \tau_{np} + \frac{1}{2} t_0. \qquad (18)$$

The Table above shows values of t_{max}, r_{max} and derived from (7) and (8) using a numerical method, and corresponding relative errors expressed in percentages when using (12), (17) and (18). The data indicate that the derived approximate formulas ensure high accuracy of calculations.

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